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HUBBLE SPACE TELESCOPE ASTROMETRIC OBSERVATIONS AND ORBITAL MEAN MOTION CORRECTIONS FOR THE INNER URANIAN SATELLITES

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ABSTRACT

The 10 small inner satellites of Uranus were discovered in 1986 with *Voyager 2* and not seen again until 1994, when eight were recovered with the *Hubble Space Telescope* Wide Field Planetary Camera 2 for astrometric, dynamical, and photometric studies. Thirty-three exposures were taken on 1994 August 14 with the PC1 chip in the *BVRI* filters. Measurable images of Ariel and Miranda were also obtained on the same CCD frames with those of the faint satellites. We present here the astrometric observations of these eight satellites relative to Miranda, as well as corrected orbital mean motions for them. For the full-well images of Ariel and Miranda, the astrometric limitation was due to an inadequate geometric distortion correction and distance from center. For the faint inner satellites, the astrometric precision varied from 50 mas for Bianca ($V = 23$ mag) to 9 mas for Puck ($V = 20$ mag) and was due primarily to a centroiding error caused by a low signal-to-noise ratio. The orbits of Owen & Synnott for the inner satellites were compared with these observations and corrections derived to their mean daily motions. While the orbits of Owen & Synnott proved to be better than their errors indicated, the new mean motions are 2 orders of magnitude more precise.

Key words: celestial mechanics, stellar dynamics — planets and satellites: individual (Uranus)

1. INTRODUCTION

Ten inner satellites of Uranus were discovered by *Voyager 2* in 1986 but not observed again until eight were detected by these observations in 1994. These satellites are an important link between the processes of formation and evolution of the Uranian ring system and its major satellites, yet very little is known about their surfaces. The brightest three of these faint satellites were within reach of the Faint Object Spectrograph of the *Hubble Space Telescope* (*HST*), but the accumulated orbital errors (Owen & Synnott 1987) were too large for accurate pointing. These satellites also show resonant relationships that are more precise than those of the outer satellites and critical to understanding the history and stability of both the rings and the satellites. However, the mean motions of the satellites could not be accurately determined from the short interval of the *Voyager 2* observations. Images were made with the Wide Field Planetary Camera 2 of *HST* in 1994 to recover as many of these inner satellites as possible and make astrometric measurements. These will provide accurate ephemerides for a spectroscopic follow-up and accurate mean motions for a detailed study of their dynamical resonances.

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2. OBSERVATIONS

Thirty-three images of the inner satellites were obtained with PC1 on 1994 August 14. Eleven exposures were taken in each of three *HST* orbits. Two orbits separated the first and second sets, while three orbits separated the second and third. This yielded good orbital coverage for all the inner satellites. To obtain some compositional information, the exposures were taken in four color filters, and to accommodate the large dynamic range, a range of exposures were taken in each filter. The distribution of exposures in each orbital set is given in Table 1.

The upper exposure limits were set by the 2 pixel motions of the inner satellites or by the blooming threshold of the planet. The middle exposure lengths were determined as the saturation limit of Ariel, while the shortest exposures were expected to be fail-safe calibration frames.

Recovery of the satellites was accomplished by electronically blinking together the two longest exposure F791W frames in each set and identifying the moving objects. The identities of the satellites were based on their relative brightnesses and on their apparent distances and position angles as predicted from the ephemerides of Owen & Synnott (1987). None of the satellites were far from their predicted position. As expected, we recovered eight of the 10 inner satellites. The epsilon-ring shepherds, Cordelia and Ophelia, were too faint and moving too rapidly for detec-

TABLE 1
EXPOSURES

Filter	Duration (s)
F439W	60, 120
F569W	10, 18, 35
F675W	8, 26, 50
F791W	12, 50, 100

tion. The two brightest of the inner satellites, Puck and Portia, were detected on all 33 frames, while the faintest, Bianca, was detected on only three. All eight of the inner satellites were detected on the F791W frames, but only the three brightest were detected on the F439W frames. In addition to the faint satellites, images of Ariel and Miranda were on all the frames. The image of Miranda was unsaturated on all frames, while that of Ariel was unsaturated on 18 frames. On 15 frames, Ariel's image had some saturation at its center, but no blooming.

3. ASTROMETRY

Our strategy for astrometric reductions was to use the most accurate ephemeris positions of Miranda and Ariel to calibrate the scale and orientation of the CCD frames and to use Miranda's image as the coordinate reference for the inner satellites. Details of our astrometric reductions are given by Pascu et al. (1997, hereafter referred to as Paper I).

The images of Miranda, Ariel, and the eight inner satellites were measured by centroiding with a two-dimensional Gaussian. A Gaussian was used since none of the images had typical point-spread functions (Paper I). Some comparisons with a Lorentz function showed differences below 0.01 pixels for Miranda. Three options were used for modeling the background: flat planar, inclined planar, and inclined quadratic. The first option was used for Miranda and Ariel, the second for moderate gradients, and the third for the most severe backgrounds near the planet.

Corrections were made for the geometric distortion in PC1 using the model of Trauger et al. (1995). While none of the three models available for correcting the distortion (Trauger et al. 1995; Holtzman et al. 1995; Gilmozzi et al. 1995) agreed within their claimed precisions (Paper I), the Trauger et al. (1995) model was the only one that accounted for the bandpass of the observations. The distortion-corrected coordinates of Miranda and Ariel were compared with a JPL ephemeris of these satellites (R. A. Jacobson 1995, private communication), and a "plate scale" and orientation correction derived for each frame. Each frame was, thus, self-calibrated, and positions for the faint inner moons are in the same reference system as that of the bright moons.

The mean scale value for all frames was $0\farcs045566 \pm 0\farcs000002$ pixel^{-1}. While the variation with filter was marginal, the variation with orientation of the line connecting Miranda and Ariel was significant and indicated incompleteness for the Trauger et al. (1995) model (see Paper I). No effect of the saturation in some of the images of Ariel was detected—probably because the saturation was minor and no blooming occurred. In Table 2, we give the positions of the eight detected inner satellites relative to Miranda. We list our file number, the midexposure time on 1994 August 14, $X = \Delta\alpha \cos\delta$, $Y = \Delta\delta$, separation, and position angle. A colon indicates that the observation was not used in the final orbital correction because it was an outlier. The outliers were at least 4 times the mean error of one observation. Out of 260 observations, five outliers (2%) were rejected.

4. CORRECTIONS TO MEAN MOTIONS

While several orbital parameters may need improvement, only the orbital mean motions can be reliably corrected with this small observational set, taken over such a limited interval. A more comprehensive improvement of the orbits should include additional observations, especially the *Voyager 2* discovery observations, which remain unpublished. Such an undertaking is planned (R. A. Jacobson 1996, private communication).

Because the calibrations were done in scale and orientation, the mean motion corrections were made in separation and in position angle so that the effects of the two calibrations on the corrections would be independent. Miranda was taken as the coordinate origin, because its image was unsaturated on all frames and it had a more accurate ephemeris than Ariel (R. A. Jacobson 1995, private communication). Positions of the faint inner satellites relative to Uranus were computed using the published orbits of Owen & Synnott (1987). The positions of Miranda and Ariel relative to Uranus were based on the GUST86 analytic ephemeris of Laskar & Jacobson (1987). Finally, computed positions of the inner satellites relative to Miranda and $O-C$, "observed" minus "computed," residuals were obtained for each observation. Conditional equations for the least-squares correction to the mean daily motion, n, for each of the eight inner satellites were of the form

$$\frac{\partial s}{\partial n}\,\Delta n = (O-C)_s$$

in separation, s, and similarly for position angle.

Solutions were made separately in separation and position angle, since incompatible solution results would indicate calibration problems. No more than three iterations were necessary. In most cases, the separation solutions agreed with the position angle solutions within their standard deviations. In no case was the difference greater than 3 standard deviations. We concluded that the calibrations were successful, and a combined solution was made; the final results are listed in Table 3. Listed are the satellite name, the V magnitude at mean opposition, the corrected mean daily motion and mean error, the number of observations used in the solution, the postsolution rms, and the Owen & Synnott (1987) mean motion with error.

5. CONCLUSIONS

In listing formal mean errors in their orbital elements, Owen & Synnott (1987) overestimated the true uncertainties in all cases. The largest residual (for Bianca) was $11\fdg5$ in orbital longitude, compared with an expected residual of 56°. The smallest residual in longitude (for Portia) was under 1°, while expected to be 10°. The salient result of Table 3 is the improvement in the mean motions by 2 orders of magnitude—due primarily to the 100-fold increase in the data arcs. Thus, the predicted positions of these satellites (except Bianca) will be accurate to about 100 mas (about 1° in orbital longitude) for the next half-century. Bianca's predictions will have this accuracy for only 10 years.

Cordelia and Ophelia, the two innermost satellites, shep-

TABLE 2

ASTROMETRIC RESULTS

Frame[a]	1994 August 14 Midexposure Time (UTC)	X (arcsec)	Y (arcsec)	Separation (arcsec)	Position Angle (deg)
Bianca:					
10B	13:30:06	9.9254	0.3611	9.9319	87.9166
20A	16:34:41	4.5153	−5.1688	6.8633	138.8608
20B	16:42:06	4.3261	−5.1567	6.7310	140.0057
Cressida:					
105	13:09:34	8.4450	−0.6159	8.4674	94.1713
10A	13:22:41	8.1496	−1.1855	8.2354	98.2769
10B	13:30:06	7.9396	−1.4823	8.0768	100.5755
208	16:28:41	3.7558	−2.9254	4.7606	127.9155
20A	16:34:41	3.7071	−2.8513	4.6768	127.5657
20B	16:42:06	3.6559	−2.7616	4.5817	127.0673
307	21:17:29	6.4987	−6.1889	8.9741	133.6010
308	21:19:41	6.5003	−6.3255	9.0700	134.2193
30A	21:25:41	6.4916	−6.6071	9.2625	135.5053
30B	21:33:06	6.3980	−6.9435	9.4417	137.3410
Desdemona:					
105	13:09:34	4.5099	−0.0655	4.5104	90.8326
107	13:14:29	4.4739	−0.0801	4.4746	91.0253
10A	13:22:41	4.3428	−0.0468	4.3430	90.6177
10B	13:30:06	4.2476	−0.0231	4.2477	90.3122
205	16:21:34	5.1811	1.5055	5.3954	73.7976
208	16:28:41	5.3003	1.5012	5.5088	74.1867
20A	16:34:41	5.4512	1.4445	5.6393	75.1583
20B	16:42:06	5.6588	1.3556	5.8189	76.5285
307	21:17:29	6.6174	−10.6860	12.5690	148.2317
30A	21:25:41	6.3134	−11.1221	12.7890	150.4189
30B	21:33:06	6.0183	−11.4088	12.8989	152.1877
Juliet:					
101	12:57:46	8.0206	−0.6523	8.0470	94.6497
102	13:01:16	7.9711	−0.7711	8.0084	95.5257
104	13:07:25	7.7234	−1.0324	7.7921	97.6136
105	13:09:34	7.7025	−1.1359	7.7859	98.3889
107	13:14:29	7.5829	−1.2978	7.6932	99.7118
108	13:16:41	7.5507	−1.3735	7.6746	100.3094
109	13:20:22	7.4997	−1.5283	7.6538	101.5178
10A	13:22:41	7.3942	−1.5802	7.5612	102.0632
10B	13:30:06	7.2120	−1.8119	7.4361	104.1026
202	16:13:16	3.7708	−1.9324	4.2371:	117.1329:
204	16:19:25	3.6609	−2.5347	4.4528	124.6977
208	16:28:41	3.5293	−2.4885	4.3184	125.1879
209	16:32:22	3.5558	−2.4222	4.3024	124.2629
20B	16:42:06	3.5335	−2.2681	4.1988	122.6960
302	21:04:16	6.4931	−5.2538	8.3524	128.9773
307	21:17:29	6.4879	−5.8711	8.7500	132.1430
308	21:19:41	6.5225	−5.9558	8.8326	132.3998
30A	21:25:41	6.4882	−6.2127	8.9830	133.7573
30B	21:33:06	6.4440	−6.6099	9.2312	135.7282
Portia:					
101	12:57:46	4.2097	0.1670	4.2130	87.7276
102	13:01:16	4.1655	0.1523	4.1683	87.9060
103	13:05:21	4.0501	0.1680	4.0535	87.6240
104	13:07:25	4.0708	0.1976	4.0756	87.2213
105	13:09:34	4.0204	0.1734	4.0241	87.5298
106	13:12:20	3.9963	0.1967	4.0011	87.1822
107	13:14:29	4.0134	0.1488	4.0161	87.8768
108	13:16:41	3.9313	0.1919	3.9360	87.2047
109	13:20:22	3.9050	0.2187	3.9111	86.7944
10A	13:22:41	3.8893	0.2211	3.8956	86.7464
10B	13:30:06	3.7960	0.2689	3.8055	85.9475
201	16:09:46	4.7890	1.6877	5.0777	70.5866
202	16:13:16	4.9029	1.7157	5.1945:	70.7137
203	16:17:21	4.9438	1.7237	5.2357	70.7786
204	16:19:25	4.9996	1.6916	5.2780	71.3066
205	16:21:34	5.0136	1.6785	5.2872	71.4901
206	16:24:20	5.0803	1.6691	5.3474	71.8123
207	16:26:29	5.1260	1.6591	5.3878	72.0649
208	16:28:41	5.1766	1.6528	5.4341	72.2921
209	16:32:22	5.2514	1.5580	5.4776	73.4753:
20A	16:34:41	5.3294	1.6234	5.5711	73.0588
20B	16:42:06	5.4867	1.5705	5.7071	74.0269
301	21:00:46	7.5719	−8.9950	11.7577	139.9099

TABLE 2—*Continued*

Frame[a]	1994 August 14 Midexposure Time (UTC)	X (arcsec)	Y (arcsec)	Separation (arcsec)	Position Angle (deg)
302	21:04:16	7.4715	−9.1324	11.7993	140.7122
303	21:08:21	7.3725	−9.3614	11.9160	141.7780
304	21:10:25	7.2933	−9.4708	11.9536	142.4009
305	21:12:34	7.2602	−9.5843	12.0237	142.8556
306	21:15:20	7.1844	−9.7309	12.0957	143.5614
307	21:17:29	7.1045	−9.8337	12.1316	144.1530
308	21:19:41	7.0403	−9.9746	12.2090	144.7846
309	21:23:22	6.9263	−10.1584	12.2950	145.7126
30A......	21:25:41	6.8563	−10.2798	12.3565	146.2979
30B......	21:33:06	6.5978	−10.6623	12.5386	148.2509
Rosalind:					
108	13:16:41	10.5901	0.7774	10.6186	85.8014
10A......	13:22:41	10.4659	0.3713	10.4725	87.9683
10B......	13:30:06	10.4247	−0.0952	10.4252	90.5230
208	16:28:41	5.4714	−6.8991	8.8053	141.5836
20A......	16:34:41	5.2570	−6.9616	8.7235	142.9418
20B......	16:42:06	5.0327	−6.9851	8.6093	144.2277
308	21:19:41	1.7826	−3.9855	4.3660:	155.9020
30A......	21:25:41	1.8212	−3.9442	4.3444	155.2147
30B......	21:33:06	1.8864	−3.9302	4.3594	154.3599
Belinda:					
107	13:14:29	2.5823	2.7225	3.7523	43.4865
108	13:16:41	2.5443	2.8160	3.7952	42.0981
10A......	13:22:41	2.6403	2.8352	3.8742	42.9610
10B......	13:30:06	2.7062	2.8912	3.9601	43.1075
205	16:21:34	5.8623	3.1832	6.6707	61.4986
207	16:26:29	6.0768	2.9895	6.7724	63.8050
208	16:28:41	6.0998	2.9553	6.7780	64.1505
20A......	16:34:41	6.2562	2.8371	6.8694	65.6060
20B......	16:42:06	6.4387	2.7238	6.9911	67.0702
302	21:04:16	8.0672	−8.6517	11.8292	137.0022
308	21:19:41	7.6283	−9.3535	12.0698	140.8011
30A......	21:25:41	7.5104	−9.7287	12.2904	142.3325
30B......	21:33:06	7.2906	−10.0844	12.4438	144.1347
Puck:					
101	12:57:46	1.7968	3.6241	4.0451	26.3719
102	13:01:16	1.8323	3.6605	4.0935	26.5906
103	13:05:21	1.8856	3.6839	4.1385	27.1053
104	13:07:25	1.9110	3.7302	4.1912	27.1264
105	13:09:34	1.9088	3.7150	4.1766	27.1944
106	13:12:20	1.9963	3.7275	4.2284	28.1717:
107	13:14:29	1.9759	3.7607	4.2482	27.7177
108	13:16:41	1.9941	3.7861	4.2792	27.7752
109	13:20:22	2.0780	3.7926	4.3246	28.7181
10A......	13:22:41	2.0827	3.8325	4.3619	28.5209
10B......	13:30:06	2.1626	3.8992	4.4588	29.0139
201	16:09:46	5.1846	3.8232	6.4418	53.5949
203	16:17:21	5.3489	3.7265	6.5190	55.1360
204	16:19:25	5.4015	3.7110	6.5535	55.5097
205	16:21:34	5.4333	3.6586	6.5503	56.0447
206	16:24:20	5.5008	3.6225	6.5864	56.6337
207	16:26:29	5.5432	3.5926	6.6056	57.0528
208	16:28:41	5.5998	3.5624	6.6369	57.5367
209	16:32:22	5.6782	3.4900	6.6650	58.4235
20A......	16:34:41	5.7274	3.4644	6.6937	58.8310
20B......	16:42:06	5.8901	3.3465	6.7744	60.3968
301	21:00:46	8.4211	−5.9216	10.2947	125.1147
302	21:04:16	8.3837	−6.0897	10.3620	125.9937
303	21:08:21	8.3411	−6.2923	10.4483	127.0300
304	21:10:25	8.3314	−6.3770	10.4918	127.4309
305	21:12:34	8.3002	−6.4860	10.5338	128.0053
306	21:15:20	8.2678	−6.6101	10.5853	128.6426
307	21:17:29	8.2433	−6.7108	10.6295	129.1488
308	21:19:41	8.2089	−6.8001	10.6596	129.6375
309	21:23:22	8.1821	−6.9742	10.7511	130.4436
30A......	21:25:41	8.1288	−7.0899	10.7863	131.0948
30B......	21:33:06	8.0127	−7.4391	10.9336	132.8739

NOTE.—Satellite positions are relative to Miranda in the sense satellite minus Miranda. Miranda postions are based on JPL's GUST86 ephemeris.

[a] The full archival *HST* frame designation is of the form U2GE0xxxT.D0D[1], where "xxx" is replaced by the number listed in the first column.

TABLE 3

MEAN MOTION CORRECTIONS

Satellite (1)	Opposition V[a] (2)	Corrected Mean Daily Motion[b] (deg day^{-1}) (3)	N (4)	rms (mas) (5)	Initial Mean Daily Motion[b,c] (deg day^{-1}) (6)
Bianca	23.0	828.387948 (0.000261)	6	70	828.3915 (0.0178)
Cressida	22.2	776.582447 (0.000022)	20	14	776.5816 (0.0035)
Desdemona	22.5	760.055518 (0.000035)	22	22	760.0532 (0.0054)
Juliet	21.5	730.126129 (0.000029)	36	23	730.1254 (0.0031)
Portia	21.0	701.486468 (0.000011)	64	16	701.4866 (0.0032)
Rosalind	22.5	644.630430 (0.000077)	18	34	644.6311 (0.0047)
Belinda	22.1	577.360308 (0.000039)	26	54	577.3628 (0.0032)
Puck	20.2	472.544556 (0.000009)	63	9	472.5451 (0.0017)

[a] From The Astronomical Almanac 1997, p. F3.
[b] Values in parentheses are mean errors.
[c] From Owen & Synnott 1987.

herd the epsilon ring (Porco & Goldreich 1987; Goldreich & Porco 1987) and are important to the study of satellite/ring dynamical interactions. Although they were not detected in these observations, they can be detected with techniques that are more costly of telescope time. This should be attempted while the rings are still open to our line of sight.

Our method of internal astrometric calibration using bright satellites worked well, but was limited by the geometric distortion corrections. There is no other obstacle to milliarcsecond astrometry of full-well images with PC1. A new distortion model is needed that better models the outer zones of PC1—especially in the I bandpasses, where detection is most efficient. For the faint satellites the situation was quite different. They were located close enough to the center of the field that distortion and calibration corrections were sufficient for milliarcsecond astrometry. However, their faintness and planetary halo involvement reduced their signal-to-noise ratio (8, at best) and, thus, their measurement precision. This can be demonstrated by plotting the opposition V magnitude of Table 3 (col. [2]) against the mean motion residual rms error (col. [5]; see Fig. 1 of Paper I). This linear relationship implies centroiding errors for the inner satellites ranging from 0.2 to 0.6 pixels on average.

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